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Ahmad Kalthoum Aluminium façades in modern construction

Fachadas de alumínio na construção moderna



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Aluminium façades in modern construction

Dissertation presented to the University of Aveiro to fulfil the necessary requirements of obtaining the master's degree in Civil Engineering, held under the supervision of Dr. Paulo Jorge de Melo Matias Faria de Vila Real, Full Professor, and the co-supervision of Dr. Nuno Filipe Ferreira Soares Borges Lopes, Assistant Professor, Department of Civil Engineering, University of Aveiro.

“We're made of star stuff. We are a way for the cosmos to know itself.”

– Carl Sagan –

o júri

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palavras-chave

Alumínio, fachada, resistência ao fogo, montante, construção moderna, preparação de obra, Eurocódigo 9, vidro, fachada cortina.

resumo

Esta dissertação tem como objetivo elaborar sistemas de fachada em alumínio e os materiais incluídos. Em complemento são apresentadas as atividades do estágio curricular realizadas durante seis meses na Martifer Alumínios, S.A.

A dissertação elabora os materiais frequentemente utilizados em sistemas de fachadas em alumínio e apresenta ainda as principais propriedades que definem as funcionalidades das fachadas que visam fornecer qualidades ao edifício como isolamento e impermeabilização.

O estágio curricular foi realizado na equipa de pré-construção da Martifer, incluindo a participação e desenvolvimento na realização de desenhos de aprovação e planos de fabrico no projeto que envolve a preparação de fachada do London Dock edifício C1.

O último capítulo desta dissertação elabora mais especificamente a resistência ao fogo de um montante de alumínio. Com base nos Eurocódigos (EN 1990, EN 1991-1-2, EN 1999-1-1, EN 1999-1-2), foram concluídas as verificações de resistência ao fogo para um montante de alumínio com e sem proteção contra incêndio.

keywords

Aluminium, façade, fire resistance, mullion, modern construction, site preparation, Eurocode 9, glass, curtain wall.

abstract

This dissertation aims to elaborate in aluminium façade systems and the materials included and presents the activities in curricular internship held over six months at Martifer Aluminios, S.A.

This dissertation focuses on the commonly used materials in aluminium façade systems and presents the main properties that defines the functionalities of façades and provides the whole building with qualities like insulation and weatherproofing.

The curricular internship was held at the pre-construction team of Martifer, it included participation and development in the realization of approval drawings and manufacturing plans of London Dock building C1 façade construction project.

The last chapter in this dissertation elaborates more specifically in fire resistance of an Aluminium mullion. Based on Eurocodes (EN 1990, EN 1991-1-2, EN 1999-1-1, EN 1999-1-2), the fire resistance verifications were concluded for the studied aluminium mullion with and without fire protection considered.

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Chapter 1

1 Introduction

1.1 General considerations

The presented dissertation has been concluded by attending a curricular internship held at Martifer Alumínios, S.A. for 6 months, and accompanied with a parallel academic study case about the fire resistance of a vertical aluminium member.

The parallel academic study case was elaborated in a real case from one of the ongoing Martifer Alumínios, S.A. projects in London, UK.

1.2 Company background

In February of 1990, Martifer Alumínios, S.A. was formed and based in the Industrial Zone of Oliveira de Frades, Viseu, where its Headquarter continues up to now.

Martifer S.A. has three business areas, Metallic Constructions, Naval Industry and Renewables. Martifer started its activity in the shipbuilding and repair sector in 2008 with the acquisition of Navalria which is a shipyard with a strategic location in Aveiro port. Martifer Renewables acts as a developer of renewable energy, mainly in wind and solar power projects, being present in five countries: in the Iberian Peninsula, Central Europe and Latin America.

Martifer Metallic Constructions provides a global and innovative solutions in metal mechanical constructions and aluminium façades. Mainly aimed at leading highly complex projects, Martifer Metallic Constructions bases its development strategy on differentiation through quality engineering. The company is focused on three major geographic areas: Europe, the Middle East and Africa, and has industrial units that allow it, from those areas, to build the most complex projects in diversified places such as in Saudi Arabia, in Algeria, or France.



Figure 1: Martifer S.A.'s Headquarter (©Martifer, 2019)

1.3 Internship objectives

The curricular internship took place in the offices of Martifer Alumínios S.A. in Martifer's Headquarter in the Industrial Zone of Oliveira de Frades, Viseu. between 11/02/2019 and 15/07/2019, 32 hours per week.

The theme of the curricular internship is "Construction site Preparation/Management", and it includes technical assistance and resources management for the construction site during the project and the execution phases.

The dissertation will be focusing on the ongoing project of London Dock building C1, a project consists of design, preparation and elaboration of the manufacturing plans of a curtain wall.

The main objective of the internship is to participate in develop the following activities:

- Technical analysis and structural design of Aluminium façades.
- Monitoring and technical-economic optimization of the construction site.
- Elaboration of aluminium façade designs for client approval.
- Preparation and modelling of manufacture plans of aluminium façades.
- Production of digital representations through designing computer software.
- Review of the commercial budget and production budgeting
- Construction site execution (productive resources management, technical preparation, analysis and/or review the project, general team coordination, billing and planning and costs control).

In addition to the internship's objectives, the academic study case is focusing and elaborating on the fire resistance of an aluminium vertical member (Mullion) for a real case from London Dock building C1 project.

1.4 Dissertation structure

Chapter -1- presents a brief background about the company where the internship takes place, the time schedule and general considerations

Chapter -2- presents an introduction about the materials used in façades and its mechanical and thermal properties. It presents also some types and solutions for façades used fabricated in Martifer Alumínios.

Chapter -3- elaborates in a specific construction site – London Dock Building C1 –, overviewing the architectural and structural point of views and presenting the series of job done for the façade design and preparation.

Chapter -4- presents a parallel academic work studying a fire action in vertical aluminium member (Mullion) in modular façade, with and without fire protection considered, verifying its stability in the resistance domain.

Chapter 2

2 Aluminium façades

A façade is a frontage of a building that faces on to a street or open space. Architecturally it's often the most important aspect from a design standpoint, as it sets the tone for the rest of the building. From the engineering perspective, the façade is also of great importance for the impact on energy efficiency.

Aluminium façade system is an outer covering of a building as non-structural exterior wall. It's typically designed with extruded aluminium framing vertical members called mullions and horizontal members called transoms infilled with glass. A non-structural wall does not carry any structural load from the building other than its own dead load weight, it's designed to resist the wind load, water infiltration and actions produced by accidental forces such as earthquakes and fire.

The wind loads are classified as variable fixed actions, it acts directly on façades and is represented by a simplified set of pressures whose effects are equivalent to the extreme effects of the wind action and calculated from the basic values of wind pressure with a mean return period of 50 years.

2.1 Materials and its properties

2.1.1 Extruded aluminium

Aluminium is a comparatively young metal, it's valued for being light, durable, flexible, impermeable, thermal conductive, relatively cheaper and non-corrosive. The energy costs for aluminium production is one of the highest costs comparing to other building materials (GRID-Arendal, 2009).

The primary source of aluminium is an ore known as bauxite that comes from surface mines in tropical and sub-tropical areas. Bauxite is usually covered by an overburden of several meters of rock and clay, which must be removed before the bauxite can be recovered. Then, the bauxite is transported to crushing or washing plants, before it is transported for processing. After a chemical treatment through the Bayer process, alumina or primary aluminium will be extracted from bauxite which then will be smelted and transformed to aluminium alloys (HARRIS, 2008).

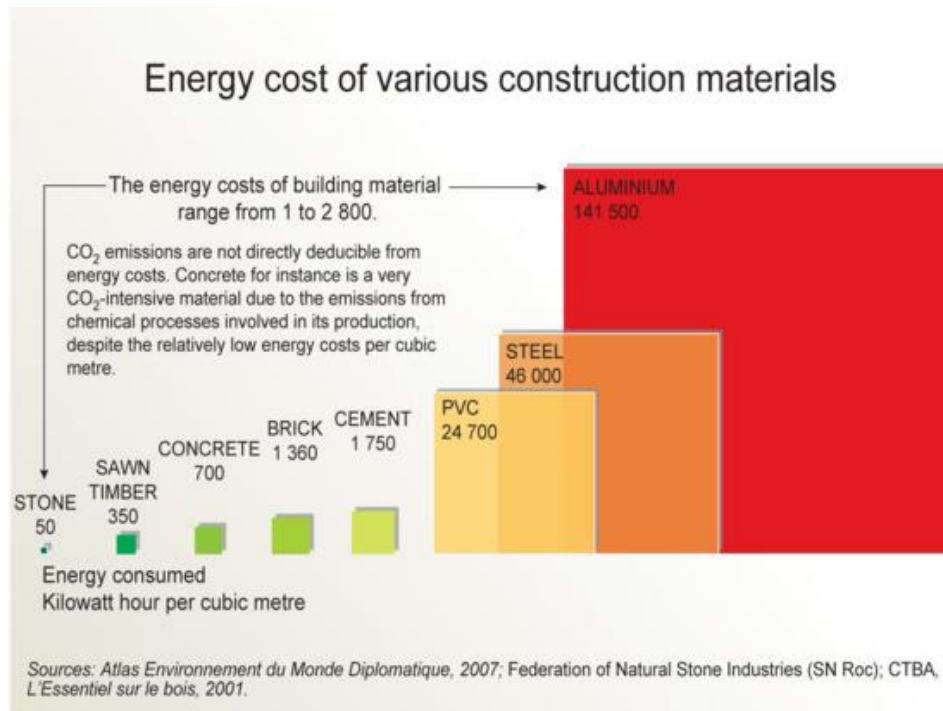


Figure 2: Energy cost of various construction materials (GRID-Arendal, 2009)

2.1.1.1 Classification of aluminium alloys

Aluminium alloys are usually classified based on the fabrication process. Casting process which aluminium is remelted and then casted. Working process where aluminium is hot worked or cold worked without being remelted such as extrusion, forging and drawing.

Aluminium alloy's reaction for the heat treatment varies based on the addition of chemical components, some chemicals such as AlMgSi, AlZnMgCu and AlCuMg added to aluminium during the fabrication process get higher strength by a heat treatment. And others such as AlMn, AlMg and AlMgMn in which strength is increased by cold working or non-heat-treatment (Mazzolani, 1994).

This designation is derived from the American nomenclature (Aluminium Association). It is now also being used in Europe in addition to the national nomenclatures. This type of nomenclature, which is used for wrought aluminium alloys, is represented by four figures. A first figure of 1 denotes those alloys in which the aluminium is greater than 99%. A first figure from 2 to 8 denotes the other alloys, the figure identifies the main alloying elements. More precisely the following correspondence Table 1 presents the different alloying elements and its designation (Mazzolani, 1994).

Table 1: Numerical Designation for wrought alloys (Mazzolani, 1994)

1XXX	Pure Aluminium (greater than 99%)
2XXX	Copper
3XXX	Manganese
4XXX	Silicon
5XXX	Magnesium
6XXX	Magnesium and Silicon
7XXX	Zinc
8XXX	Other elements
9XXX	Unused series

In the first group (1XXX) the third and the fourth figures indicate the percentage of aluminium above 99%, e.g. 1070 alloy has an aluminium content of 99.70%. The second figure represents the level of impurities, and it's equal to 0 if the impurities are uncontrolled, and it can vary between 1 and 9 depending upon the level which the impurity content is not to exceed. In the other groups, the second figure is equal to 0 for the main alloy and varies between 1 and 9 for its modifications. The third and fourth figures identify together the specific alloys within each group (Mazzolani, 1994).

The Aluminium Association also utilizes the numerical designation for casting alloys, with the following meaning in Table 2.

Table 2: Numerical Designation for casting alloys (Mazzolani, 1994)

1XXX	Pure Aluminium (greater than 99%)
2XXX	Copper
3XXX	Silicon + Copper and/or magnesium
4XXX	Silicon
5XXX	Magnesium
6XXX	Unused series
7XXX	Zinc
8XXX	Tin
9XXX	Other elements

This European standard covers the design of structures fabricated from aluminium alloy material listed in Table 3 for some wrought alloys.

Table 3: Wrought aluminium alloys for structures (EN1999-1-1, 2007)

Alloy designation		Form of product
Numerical	Chemical symbols	
EN AW-3004	EN AW-AlMn1Mg1	SH, ST, PL
EN AW-5454	EN AW-Al Mg3Mn	SH, ST, PL, ET, EP, ER/B
EN AW-6060	EN AW-Al Mg Si	ET, EP, ER/B, DT
EN AW-6063	EN AW-Al Mg0.7Si	ET, EP, ER/B, DT
EN AW-6082	EN AW-Al Si1MgMn	SH, ST, PL, ET, EP, ER/B, DT, FO
SH - Sheet (EN 485) ST - Strip (EN 485) PL - Plate (EN 485) ET - Extruded Tube (EN 755) EP - Extruded Profiles (EN 755)		DT - Drawn Tube (EN 754) FO - Forgings (EN 586) ER/B - Extruded Rod and Bar (EN 755)

2.1.1.2 Heat treatment process

The main phases of the heat treatment start with heating up to 450 or 530 °C depend on the alloy, then tempering with water or air and then aging which can be natural or artificial. The last phase in the process will give the aluminium alloy an additional designation that describes its aging. Natural aging which occurs spontaneously at room temperature takes the designations (T1, T2, T3 and T4). Artificial aging happens with prescribed time and temperature until aluminium reaches a stable condition and it takes the designation (T5, T6 and T9) (Mazzolani, 1994).

The Letter T refers to Solution Heat Treatment, used for aluminium that has been strengthened by heat treatment, with or without subsequent strain hardening, followed by one or more numbers elaborated below. In addition to that Annealing takes the designation O and it's used after cold working to soften work-hardening alloys (1XXX, 3XXX and 5XXX). Strain hardened treatment with the letter H, applied to wrought alloys only Used for products that have been strengthened by strain hardening, with or without subsequent heat treatment (Mazzolani, 1994).

- T1** - Cooled from an elevated temperature process and naturally aged.
- T2** - Cooled from an elevated temperature process, cold worked, and naturally aged.
- T3** - Solution heat treated, cold worked, and naturally aged.
- T4** - Solution heat treated, and naturally aged.
- T5** - Cooled from an elevated temperature process then artificially aged.
- T6** - Solution heat treated then artificially aged.
- T7** - Solution heat treated then overaged/stabilized.
- T8** - Solution heat treated, cold worked, then artificially aged.
- T9** - Solution heat treated, artificially aged, then cold worked.
- T10** - Cooled from an elevated temperature process, cold worked, then artificially aged.

2.1.1.3 Extrusion process

Extrusion is defined as the process of shaping material, such as aluminium, by forcing it to flow through a shaped opening in a die. Extruded material emerges as an elongated piece with the same profile as the die opening. The die is a steel disk with an opening, the size and shape of the requested cross-section of the final extruded member. The main advantage of this process over other manufacturing processes are its ability to create very complex cross-section. Temperature is most critical because it gives aluminium its desired characteristics such as hardness and finish. Aluminium can be hot or cold extruded. Aluminium hot extruded is heated to 300 to 600 °C, and it is done above the material's recrystallization temperature to keep the material from work hardening and to make it easier to push the material through the die. Cold extrusion is done at room temperature or near room temperature. The advantages of this over hot extrusion are the lack of oxidation, higher strength due to cold working, closer tolerances and better surface finish (Aluminum, 2019).

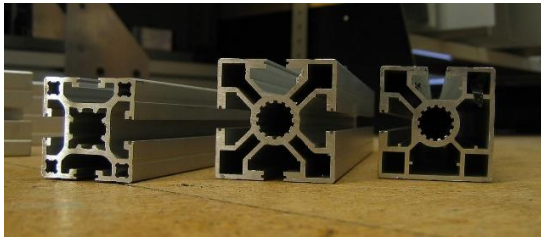


Figure 3: Extruded aluminium cross-section (Shah, 2015)



Figure 4: Extrusion die (©MetraSPA, 2019)

2.1.1.4 Mechanical behaviour of cross-sections

Referring to the global behaviour of a cross-sections, regardless of the internal action considered (axial load, bending moment or shear), the following limit states can be defined as in Ref. (EN1999-1-1, 2007):

Elastic buckling limit state is related to the strength corresponding to the onset of local elastic instability phenomena in the compressed parts of the section.

Elastic limit state is related to the strength corresponding to the attainment of the conventional elastic limit f_0 of material in the most stressed parts of the section.

Plastic limit state is related to the strength of the section, evaluated by assuming a perfectly plastic behaviour for material with a limit value equal to the conventional elastic limit f_0 , without considering the effect of hardening.

Collapse limit state is related to the actual ultimate strength of the section, evaluated by assuming a distribution of internal stresses accounting for the actual hardening behaviour of material.

Cross-sections can be classified according to their capability to reach the above defined limit states, and it can be divided as in Figure 5.

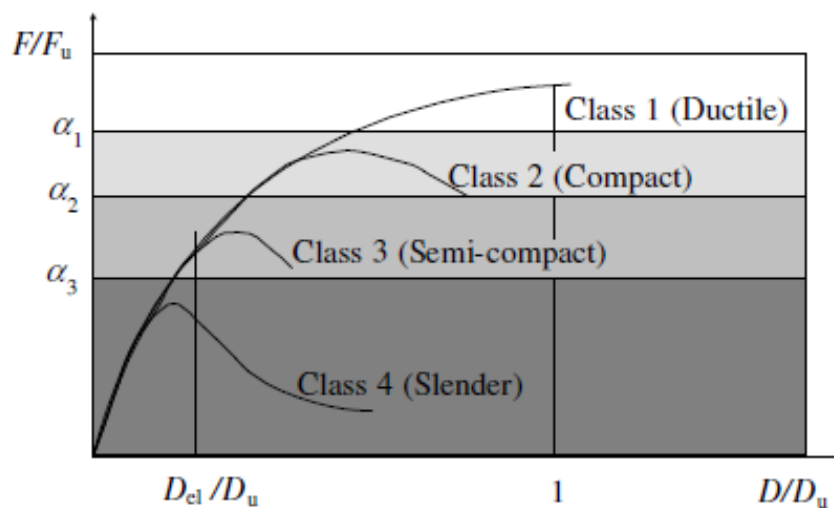


Figure 5: Classification of cross-sections (EN1999-1-1, 2007)

2.1.1.5 Mechanical material properties

According to Annex E in EN 1999-1-1 the analytical characterization of the stress (σ) – strain (ϵ) relationship of an aluminium alloy can be done by means of one of the following models:

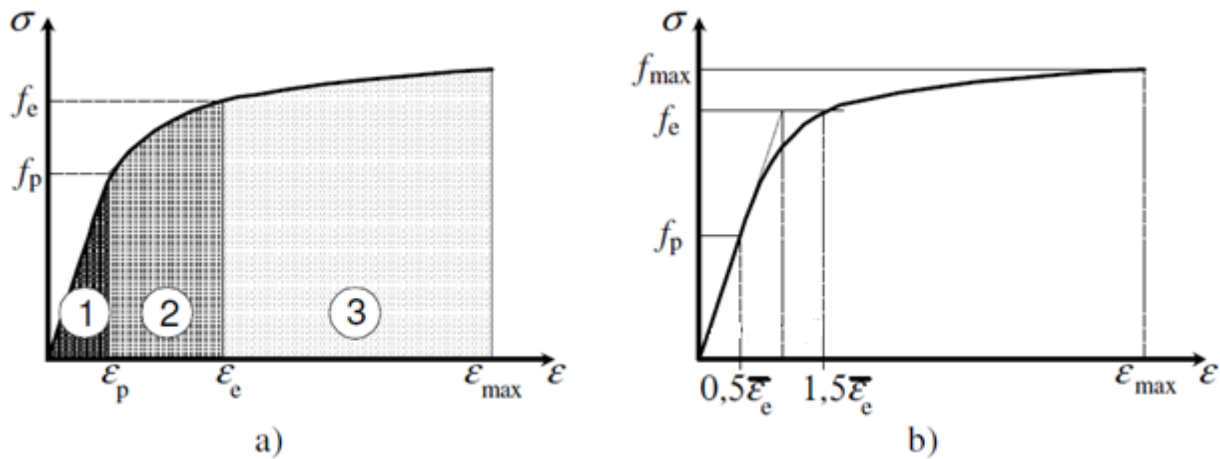
Piecewise models: these models assume that material σ - ϵ law is described by means of multi linear curve, each branch of it representing the elastic, inelastic and plastic, with or without hardening, region respectively.

Continuous models: These models assume that the material σ - ϵ law is described by means of a continuous relationship representing the elastic, inelastic and plastic, with or without hardening, region respectively.

$\sigma = \sigma(\epsilon)$ law is assumed, it is convenient to identify three separate regions which can be defined in Figure 6 a) divided for elastic, inelastic and strain-hardening behaviour, respectively. In each region the behaviour of the material is represented by means of different stress vs. strain relationships, which must ensure continuity at their limit points. According to this assumption, the characterization of the stress-strain relationship may be expressed as follows Figure 6 b).

Table 4: Regions of material behavior (EN1999-1-1, 2007)

Region 1 Elastic	$\sigma = E \varepsilon$	$0 < \varepsilon \leq \varepsilon_p$	$\varepsilon_p = 0,5 \overline{\varepsilon_e}$ and $\overline{\varepsilon_e} = f_e/E$
Region 2 Inelastic	$\sigma = f_e \left[-0,2 + 1,85 \frac{\varepsilon}{\overline{\varepsilon_e}} - \left(\frac{\varepsilon}{\overline{\varepsilon_e}} \right)^2 + 0,2 \left(\frac{\varepsilon}{\overline{\varepsilon_e}} \right)^3 \right]$	$\varepsilon_p < \varepsilon \leq 1,5 \overline{\varepsilon_e}$	$\varepsilon_p = 0,5 \overline{\varepsilon_e}$ and $\overline{\varepsilon_e} = f_e/E$
Region 3 Strain-hardening	$\sigma = f_e \left[\frac{f_{max}}{f_e} - 1,5 \left(\frac{f_{max}}{f_e} - 1 \right) \frac{\overline{\varepsilon_e}}{\varepsilon} \right]$	$1,5 \overline{\varepsilon_e} < \varepsilon \leq \varepsilon_{max}$	
f_e = conventional elastic limit f_{max} = tensile strength at the top point of $\sigma - \varepsilon$ curve ε_e = strain corresponding to the stress f_e ($\varepsilon_e = 1,5 \overline{\varepsilon_e}$) ε_{max} = strain corresponding to the stress f_{max} E = elastic modulus			

Figure 6: Continuous models in the form $\sigma = \sigma(\varepsilon)$ (EN1999-1-1, 2007)

According to experimental data in (EN1999-1-1, 2007) the nominal values of the ultimate strain (ε_u) for the several alloys could be calculated using an analytical expression obtained by means of interpolation of available results. This expression, which provides an upper bound limit for the elongation at rupture, can be synthesized by the following expressions:

$$\varepsilon_u = 0,3 - 0,22 \frac{f_o(N/mm^2)}{400} \quad \text{if } f_o < 400 \text{ N/mm}^2$$

$$\varepsilon_u = 0,08 \quad \text{if } f_o \geq 400 \text{ N/mm}^2$$

Table 5 presents the principal mechanical and physical characteristics of pure aluminium without considering elevated temperature.

Table 5: Mechanical and physical characteristics of pure aluminium

Propriety		Observations
Linear thermal expansion coefficient (α)	$23.5 \times 10^{-6} / ^\circ\text{C}$	-
Elastic modulus (E)	70 GPa	Until 100 °C
Poisson coefficient (ν)	0.33	-
Shear modulus (G)	26 GPa	$G = E / [2(1 + \nu)]$
Yield strength (f_{yk})	≤ 25 MPa	-
Tensile strength (f_{uk})	≤ 58 MPa	-

For European standards based on EN 1999-1-1, Table 3.2 a, b and c mentions the characteristic values of 0.2% proof strength f_0 , ultimate tensile strength f_u for unwelded and HAZ (Heat Affected Zone) for wrought aluminium alloys. Also, in EN 1999-1-1 Table 3.3 it's mentioned the characteristic values of 0.2% proof strength f_0 , ultimate tensile strength f_u for cast aluminium alloys – Gravity castings.

The elasticity modulus or Young's modulus (E) is the ratio of stress to strain, and for aluminium until 100 °C it's 70 GPa. Comparing to steel, aluminium presents 3 times lower Young's modulus, it means most alloys of aluminium dent or scratch more easily as compared to steel. On other side, steel with having a linear thermal expansion coefficient 2 times lower than aluminium, it is less likely to warp, deform or bend under heat, weight or force.

Aluminium alloys are classified with their specific heat treatment and strength including characteristic values of ultimate tensile strength (f_u) and 0.2% proof strength (f_0), taking to consideration the section's thickness. Table 6 contains some wrought alloys for extruded profiles and its mechanical properties, when all the alloys classification can be found in table 3.2a and 3.2b in (EN1999-1-1, 2007).

Table 6: Alloys and characteristic values (EN1999-1-1, 2007)

Alloy EN-AW	Temper	Thickness (mm)	f_0 (MPa)	f_u (MPa)
6060	T5	$t \leq 5$	120	160
		$5 < t \leq 25$	100	140
	T6	$t \leq 15$	140	170
		$t \leq 20$	160	215
6063	T5	$t \leq 3$	130	175
		$3 < t \leq 25$	110	160
	T6	$t \leq 25$	160	195
		$t \leq 20$	190	220

2.1.1.6 Thermal behaviour

Aluminium like any other metal behaves differently with the rise of temperature, it functions with its normal mechanical characteristic in room temperature, and with elevated temperatures the tensile properties reduces in a relation to temperature and nonuniformly. According to (EN1999-1-2, 2007) and after 2 hours of thermal exposure to elevated temperature, $E_{al,\theta}$ which is Young's modulus for all aluminium alloys at elevated temperatures decreases, represented in Figure 7. Aluminium suffers also aluminium elongation during the increasing of temperature.

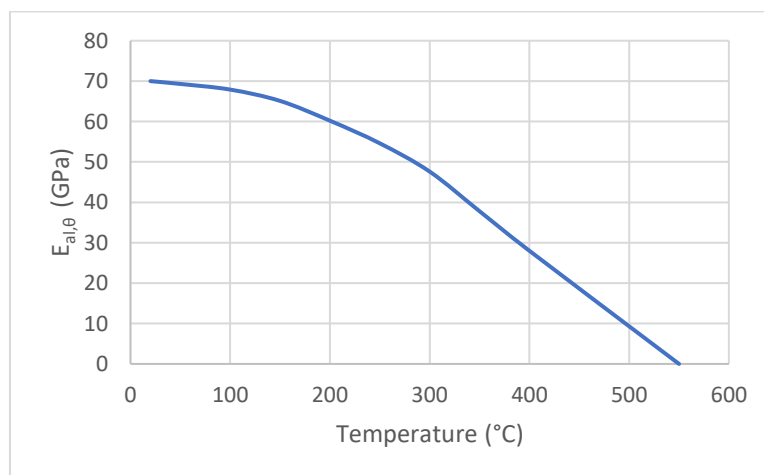


Figure 7: Modulus of elasticity of aluminium alloys at elevated temperature (EN1999-1-2, 2007)

The capacity of transferring or absorbing energy is presented by a physical quantity called the specific heat, and it's the amount of heat per unit mass required to raise the temperature by one degree Celsius. Aluminium's specific heat capacity in 20 °C is 911.2 J/ (kg. °C), however it varies with the increasing of the temperature. This relationship is specified in EN 1999-1-2 through the following equation and illustrated in Figure 8.

$$c_{al} = 0.41 \theta_{al} + 903 \text{ (J/ (kg. °C))} \quad (1)$$

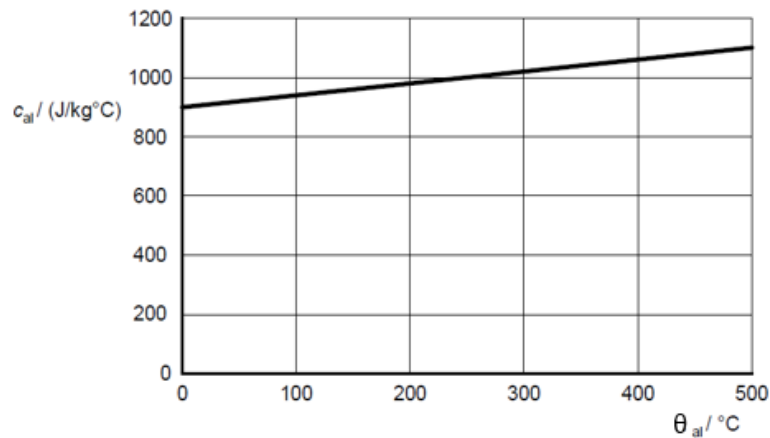


Figure 8: Specific heat of aluminium alloys as a function of the temperature (EN1999-1-2, 2007)

The variation of the relative thermal elongation with the temperature determined from the following expression and illustrated in Figure 9. where, Δl is the temperature induced elongation and l is the length at 20 °C.

$$\Delta l/l = 0.1 \times 10^{-7} \times \theta_{al}^2 + 22.5 \times 10^{-6} \times \theta_{al} - 4.5 \times 10^{-4} \quad (2)$$

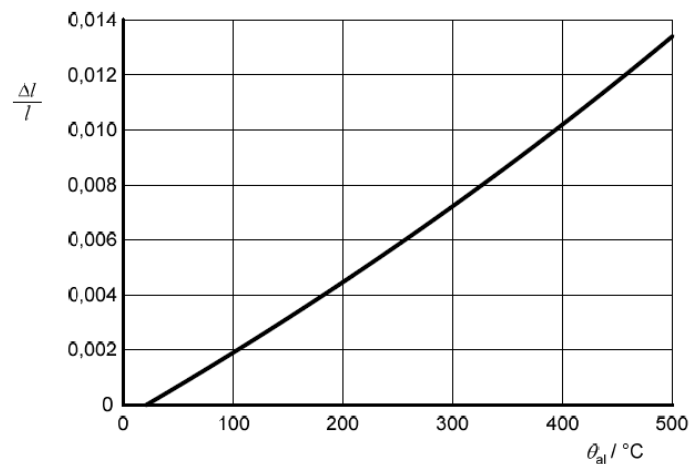


Figure 9: Relative thermal elongation of aluminium alloys as a function of the temperature (EN1999-1-2, 2007)

The mechanical properties of aluminium alloys that have been mentioned before are considered at 20 °C, which is the normal temperature design. In case of fire or a temperature rise, aluminium behaves according to the material temperature, its properties changed such as strength and deformation.

According to (EN1999-1-2, 2007), for thermal exposure up to 2 hours, the 0,2% proof strength at elevated temperature of the aluminium alloys listed in Table 7, follows from:

$$f_{o,\theta} = k_{o,\theta} * f_o \quad (3)$$

where, f_o , θ is 0,2 proof strength at elevated temperature and $k_{o,\theta}$ is 0,2 proof strength ratio, its values for some aluminium alloys are listed in Table 1a in EN 1999-1-2, some values with different temperatures is mentioned in Table 7.

Table 7: 0,2% proof strength ratios $k_{o,\theta}$, for aluminium alloys at elevated temperature for up to 2 hours thermal exposure period (EN1999-1-2, 2007)

Alloy	Temper	Aluminium alloy temperature °C							
		20	100	150	200	250	300	350	550
EN AW-5454	H34	1,00	1,00	0,85	0,58	0,34	0,24	0,15	0
EN AW-6061	T6	1,00	0,95	0,91	0,79	0,55	0,31	0,10	0
EN AW-6063	T5	1,00	0,92	0,87	0,76	0,49	0,29	0,14	0
EN AW-6063	T6	1,00	0,91	0,84	0,71	0,38	0,19	0,09	0

2.1.1.7 Aluminium contact with other materials

Aluminium has excellent corrosion resistance even in very aggressive environments. This characteristic is from its reaction with oxygen. The contact with oxygen causes the formation of aluminium oxide layer on the surface which works as a protective layer. There are, however, some precautions to be taken in special circumstances which are related with the following cases adapted from Ref. (Camposinhos, 2013).

The electric potential difference, in mV, between aluminium and other metals is variable. Therefore, the contact between aluminium and so-called “electropositive” metals in humid environments may cause the stack effect. So, the contact between aluminium and metals such as magnesium, lead, copper, steel, stainless steel and other more noble metals such as silver and platinum. The presence of an electrolyte, such as sea water or humidity in industrial environments

can produce localized harmful effects. Steel screws should be galvanized, but it is always preferable to use screws made of aluminium or stainless-steel alloys.

The presence of gypsum or cement in humid environments, causes a major superficial attack in aluminium leaving white spots that are indelible. These spots do not have any influence on the resistance. While working with gypsum or cement around aluminium windows frames, they must be protected by insulating tapes to avoid the contact.

Most of dry wood has no reaction on aluminium, however, certain woods in the presence of water or humidity react to acidic substances that effect aluminium. It is recommended that wood should be previously painted before its contact with aluminium.

2.1.2 Glass

In architecture and construction, glass has many useful properties such as energy efficiency and acoustic control, glass provide coating to the building that prevent heat escaping through the windows. And the air barrier also enhances acoustic control. It's also a brittle material with ability to resist deformation under load. Transparency is a property that allow visual connection with the outside world. Its transparency can be permanently altered by adding admixtures to the initial batch mix. By the advent of technology clear glass panels used in buildings can be made opaque (Electro chromatic glazing).

Glass is a fragile material and perfectly elastic, it means that it does not present permanent deformation. The following Table 8 presents some mechanical properties of glass.

Table 8: Mechanical properties – Glass (Savić, 2013)

Density	2.4	Kg/m ³
Compressive strength	≥ 69 (Tempered Glass)	MPa
Flexural strength	120 – 200 (Tempered Glass)	MPa
Young's module	70	GPa



Figure 10: Glass with air barrier in aluminium frame (India business directory, 2019)

The following are glass types that are made with different qualities to enhance their performance adapted from Ref. (Savić, 2013):

Annealed glass is the most commonly used glass, annealing is the process of slowly cooling glass to relieve internal stresses and avoid distortion, this process leads to a good surface flatness for the glass. On the other side this type of glass breaks into sharps which make it dangerous.

Heat-strengthened glass has at least twice the strength and resistance to breakage from wind loads or thermal forces comparing to annealed glass. But like annealed glass it can break into large sharps.

Fully tempered glass has at least four times the strength and a breakage resistance of annealed glass, it has been heated and rapidly cooled, increasing its strength and ductility. In breakage scenario, fully tempered glass breaks into small fragments, which makes it suitable as safety glazing under certain conditions like high wind pressure or extreme heat or cold.

Laminated glass is a type of safety glass that holds together when shattered. In the event of breaking, it is held in place by an interlayer, typically of polyvinyl butyral (PVB) between its two or more layers of glass. The interlayer keeps the layers of glass bonded even when broken, and its high strength prevents the glass from breaking up into large sharp pieces. It is a durable and versatile glass with plastic interlayer which provides protection from ultraviolet rays and attenuates vibration and gives laminated glass good acoustical characteristics. Can be used in a variety of environments.

Insulating glass also known as double glazing consists of two or three glass panes separated by an airspace that can be filled during the manufacturing process with either dry air or a low-conductivity gas. The thermal performance of double glazing can be further improved by the addition of a low-emissivity coating on the layers of glass. The air space also reduces heat gain and loss, as well as sound transmission, which gives the insulating glass superior thermal performance and acoustical characteristics compared to single glazing.

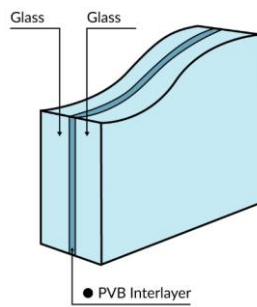


Figure 11: Laminated glass with PVB interlayer
(Glazcon, 2018)

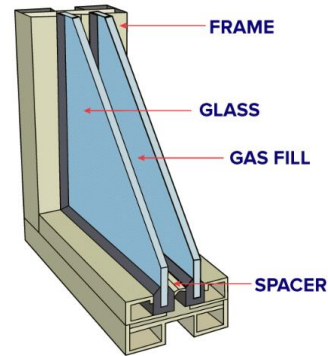


Figure 12: Insulated Glass Unit known as IGU
(Glazcon, 2018)

Coated glass is covered with reflective or low-emissivity (low-E) coatings. In addition to providing aesthetic appeal, the coatings improve the thermal performance of the glass by reflecting visible light and infrared radiation.

Wired glass is a glass reinforced with rolled steel wires, inserted during the manufacturing of plate glass allowing the glass to adhere together when cracked. It can qualify as safety glass for some applications.

Due to the low thermal conductivity of the glass ($0.8 \text{ W/(m} \cdot ^\circ\text{C)}$), heating or partial cooling of a glass causes forces within the glass that can cause rupture, called thermal breakage. The most frequent thermal breakage occurs when the edges of a glass which is contained within the frame experiences a thermal exposure causing slower heating than the surface of the glass.

2.1.3 Steel

Steel is an alloy consisting mainly of iron with an addition of carbon content varies between 2.0 – 2.1 % of its weight. Adding carbon to iron increases its strength. This variety of properties such as toughness, ductility, weldability, durability, recyclability gives steel a wide spectrum of uses.

Steel is used in many ways in an aluminium façade, taking advantage of its strength, its resistance to fire. Steel Brackets are used to support aluminium modules, fixing the elements of the façade and transfer the façade weight to the slab. Brackets can take many shapes based on the condition of installation.

2.1.3.1 Structural steel properties

Structural steel differs from concrete in its attributed compressive strength as well as tensile strength. For properties like, having high strength, stiffness, toughness, and ductile properties, structural steel is one of the most commonly used materials in commercial and industrial building construction.

Structural steel can be developed into nearly any shape, which are either bolted or welded together in construction. It can be erected as soon as the materials are delivered on site, making steel a schedule-friendly construction material.

Steel is inherently a noncombustible material. However, with temperature rise in a fire scenario, the strength and stiffness of the material is significantly reduced. The International Building Code requires steel be enveloped in sufficient fire-resistant materials.

Structural steel is mechanically classified according to EN 1993-1-1 (Table 3.1) by the nominal value of yield strength f_y and the ultimate strength f_u , based on the manufacturing process, standards, type of steel alloy and thickness. The designation of steel starts with the letter S for Steel, then it's followed by number that represents its yield strength, like S235.

Table 9: Design values for Structural steel Coefficients (EN1993-1-2, 2005)

Elasticity modulus – E	210	GPa
Shear modulus – G	81	GPa
Poisson ratio in elastic stage - ν	0.3	
Linear thermal expansion coefficient - α	12×10^{-6}	Per K (for $T \leq 100^\circ\text{C}$)

Specific heat capacity for steel varies with temperature rise, however, in 1995 edition of EN 1993-1-2 and for simplified calculations, C_s can be considered 600 J/(kg.K) independently of steel's temperature (Vila Real, Incêndio em Estruturas Metálicas, 2003).

$$c_s = \begin{cases} 425 + 7.73 \times 10^{-1} \times \theta_s - 1.69 \times 10^{-3} \times \theta_s^2 + 2.22 \times 10^{-6} \times \theta_s^3 & \text{for } 20^\circ\text{C} \leq \theta_s < 600^\circ\text{C} \\ 666 + \frac{13002}{738 - \theta_s} & \text{for } 600^\circ\text{C} \leq \theta_s < 735^\circ\text{C} \\ 545 + \frac{17820}{\theta_s - 731} & \text{for } 735^\circ\text{C} \leq \theta_s < 900^\circ\text{C} \end{cases} \quad (\text{J/kgK}) \quad (4)$$

For temperatures between 900 and 1200 °C the value of specific heat capacity is 650 J/(kg.K) .

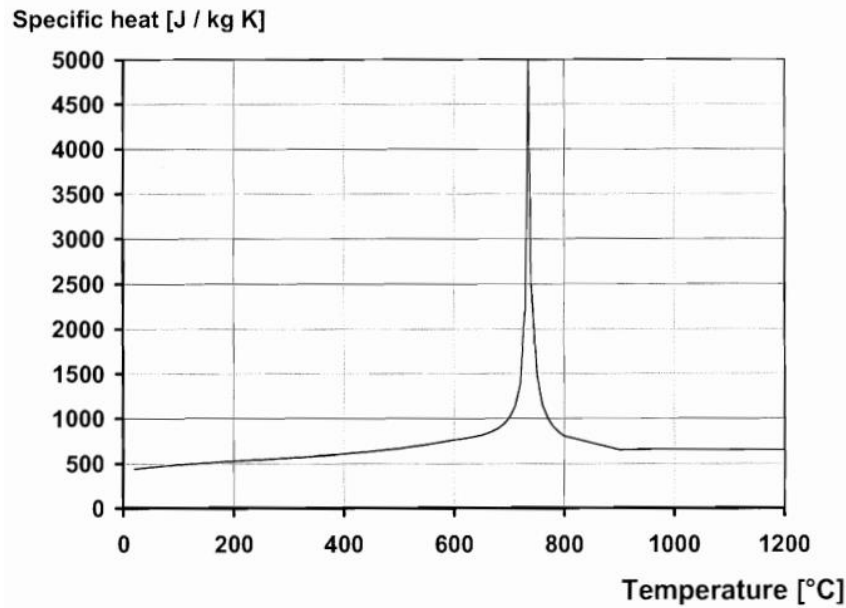


Figure 13: Specific heat capacity of Structural steel as a function of the temperature (EN1993-1-2, 2005)

Thermal conductivity of Steel is also given in EN 1993-1-2 as a function of steel temperature, for temperatures between 20°C and 800°C λ_s equals to $54 - 3.33 \times 10^{-2} \times \theta_s$ (W/(m.K)), and for temperatures between 800°C and 1200°C, the value is 27.3 (W/(m.K)).

Relative thermal elongation of Structural steel is also a function of steel temperature according to EN 1993-1-2, given in the following expression, where l is the element initial length in 20 °C.

$$\Delta l/l = \begin{cases} 1.2 \times 10^{-5} \times \theta_s + 0.4 \times 10^{-8} \times \theta_s^2 - 2.416 \times 10^{-4} & \text{for } 20^\circ\text{C} \leq \theta_s < 750^\circ\text{C} \\ 1.1 \times 10^{-2} & \text{for } 750^\circ\text{C} \leq \theta_s < 860^\circ\text{C} \\ 2 \times 10^{-5} \times \theta_s - 6.2 \times 10^{-3} & \text{for } 860^\circ\text{C} \leq \theta_s < 1200^\circ\text{C} \end{cases} \quad (5)$$

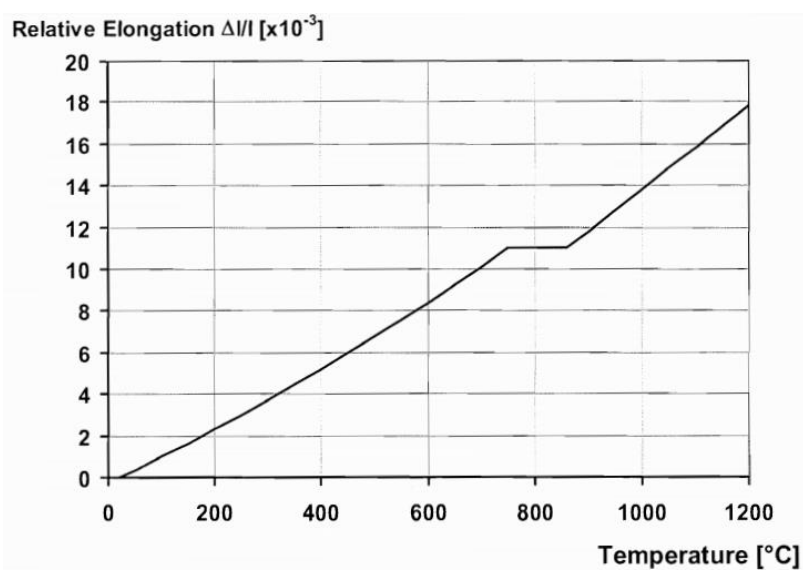


Figure 14: Relative thermal elongation – Steel (EN1993-1-2, 2005)

2.1.3.2 Steel bracket

Steel brackets in façades are supporting members attached to the slab to transfer the module loads to it. It takes several shapes depend on the conditions of installing and its required resistance. Brackets are connected to the body of the module by string of weld or bolts through screw holes in a galvanized steel sheet that support the rest of the module members. The connection with the slab is done by bolts attached to the Cast-in Channel.

Cast-in Channel system is a fixing system consists of rolled steel elements that are cast into concrete structure, provided with bolts designed to hold the module through its bracket. Cast-in channel are installed during the structure execution phase. Advantages like, high load capacity, fixing without damaging concrete, the easy installation and the absence of drilling make this system a useful and a common solution for façades projects.



Figure 15: Cast-in Channel connected to the reinforcement (©Hilti, 2019)

2.1.3.3 Galvanized Steel Sheet

Galvanizing is a zinc coating applied to steel sheets, a process in which steel sheet passes in a bath of molten zinc. The bond between liquid zinc and iron in steel forms a protective layer. The finished product resists corrosion without any additional painting or coating making galvanized steel sheet the most economical process to protect steel from corrosion (Hornbacher, 2019).

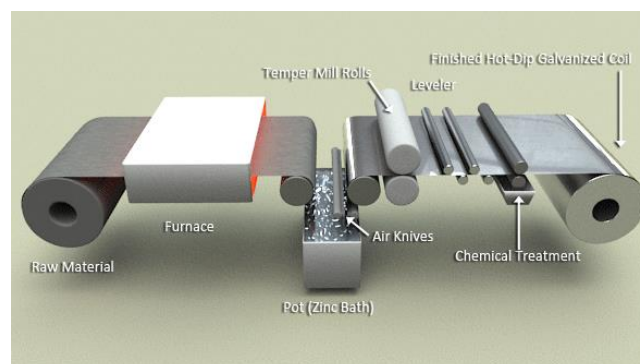


Figure 16: Galvanizing Process (Group Flat Roll, 2019)

2.1.4 Glass Reinforced Concrete – GRC

GRC is composite material, consists of mixing cement and sand reinforced with glass fibers. It is commonly used in cladding of modern façades. Its light weight makes it one of the best solutions for reducing dead load on the building and its density is between 1.9-2.1 ton per m³ (Spray up GRC). The design of GRC panels uses a knowledge of its basic properties under tensile, compressive, bending and shear forces, coupled with estimates of behavior under secondary loading effects such as thermal response and water infiltration.

Spray is one of the manufacturing methods of GRC, starts with high shear mixing of water and admixture (and polymer if used), then sand/cement slowly added to the mixture until a smooth creamy slurry is achieved by reaching to a specific consistency. After that the mixture is transferred to a pump provided with a spray gun to be projected to a mold surface using an air supply from a compressor. Some mixtures need 7 days of curing after projecting. if a polymer curing compound is used in the mixture, the units can be exposed to the atmosphere immediately although it is advisable to keep them protected from direct sunlight or external conditions for a day or two.

Premix is another manufacturing method of GRC, where sand/cement and glass fibers are pre-mixed. The production using this method can involve several technics like injection or vibration. When the mixture is ready, it's poured into mold which is vibrated to liberate air from inside the mixture.

The curing of these composites should be done by a wet process in which the pieces after demolding are introduced into a steam oven or by the introduction of polymers into the blend.

Table 10: GRC - Mechanical properties (WikiMartifer, 2019)

Properties	Spray up	Premix	
Density	1.9 – 2.1	1.8 – 2.0	t/m ³
Compressive strength	50 – 80	40 – 60	MPa
Elasticity modulus	10 – 20		GPa

In terms of thermal function, GRC's thermal conductivity coefficient varies between 0.5 and 1.0 W/(m.°C), and this physical property makes GRC a good thermal insulation. It also provides the building with acoustic insulation, for a panel of GRC with 10mm thickness there will be an acoustic reduction of 20 to 30 dB (WikiMartifer, 2019).



Figure 17: Spraying process (WikiMartifer, 2019)



Figure 18: Premix process (WikiMartifer, 2019)

2.2 Types of façades

Technological developments have completely changed the concept of façades. Until very recently the façade only represented a separation between the exterior and the interior. Now, it acts as an active module that will have to interact in the best way with extreme climatic conditions, with the effect of transparency, ventilation, heat and noise pollution.

The following types of façades are the type of façades designed, developed and fabricated in Martifer Aluminios different projects. The following mentioned façade's definitions and characteristics are adapted from Ref. (WikiMartifer, 2019).

2.2.1 Curtain wall

The curtain façade consists of an aluminum and glass system integrated in the new architecture concepts for buildings. This system guarantees the specific functionalities of the project in structural terms and of air permeability, water tightness and mechanical resistance to the wind action.

The composition of the curtain wall system includes resistant elements, filler elements, machined elements and fixing elements. Table 11 explains the elements of each group, their designation and function.

Table 11: Composition of curtain wall (WikiMartifer, 2019)

Elements	Composition	Designation/function
Resistant	Mullion (Vertical)	Fixed to the building structure. Supports its own weight, other fixed elements weight and wind load on façade.
	Transom (Horizontal)	Fixed to mullions. Supports the loads of the filler materials (Glass, panels, etc.).
Filler	Glass	Allows the entry of light for the transparent type of glass
	Opaque panels	Placed in blind zones. Consists of sandwich panels or aluminium sheets.
Machined	Windows	consists of built-in windows to facilitate ventilation and/or building maintenance. It may also contribute to safety in the event of smoke evacuation and emergency access.
Fixing	Brackets	Usually in steel, support the curtain façade to the structure of the building. They contain adjustment elements that correct the fixation in the three axes.
	Bolts	Used to bind all the connection points between mullions and transoms.

Curtain walls can be classified structurally according the construction system, it can be continuous, when the façade passes in front of the slab or interrupted, when it is between the slabs.

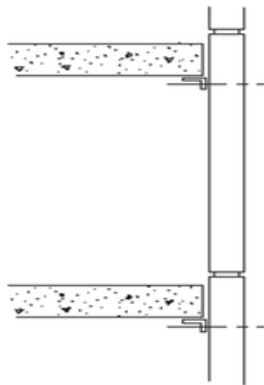


Figure 19: Continuous curtain wall (WikiMartifer, 2019)

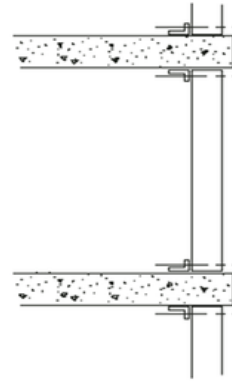


Figure 20: interrupted curtain wall (WikiMartifer, 2019)

In terms of installation curtain walls can be modular, traditional and semi-modular. Modular systems or framed systems are fabricated in finished modules including the filling of glass, windows, doors and buckling parts to install in the site. Each module in these systems are structurally independent of the remaining modules, and its height coincides with the distance between the slabs. Traditional systems are fabricated from mullions, transoms and other fixation members installed in the site. Semi-modular systems are a combination of the two previous types of systems.

2.2.1.1 Modular façade (Unitized system)

Modular façade is formed by modular units contains all the necessary components for its manufacturing and installation. The fixing notches are incorporated into the perimeter, ensuring ease of handling during transport and offloading at the site. During manufacturing phase these units are produced with a quality that can be strictly controlled. The installation process requires less time than the traditional type of façades, where units have to be lifted by crane to be fixed in its position which is more efficient than scaffolding.

Advantages

- Flexibility
- Don't require scaffolding
- High quality of assembly in factory
- Effective watertight between the units
- Supports larger joint movements

Disadvantages

- Requires a specialized manpower
- Elevated costs



Figure 21: The Installation of modular façade (@Martifer, 2019)

2.2.1.2 Traditional façades (Stick system)

The traditional curtain façades result from the combination of glass panels with aluminium members visible from outside, where the vertical and horizontal members are well defined. In this system the glazing is performed by back cape that fix the glass to the supporting structure. The clamping cap (vertical and horizontal) is protected by an outer cape, fixed by clipping. The outer shells and the clamping shells are insulated from the glass through an EPDM insulation profile (outer seals) as well as the inner frame (inner seals). This is made up of aluminum profiles that form the uprights and has drainage and ventilation channels that guarantee, together with the EPDM joints system, the weathertightness and permeability of the System.

Advantages

- Common solution
- Low cost
- Fast execution at the site
- Ease delivery for extra members

Disadvantages

- The need for scaffolding
- Elevated assembly duration

- Difficult quality control for assembly
- The need for storage at the site
- Outsider fixing for glass



Figure 22: Traditional façade system (WikiMartifer, 2019)

2.2.1.3 Façade type Aufsatz

Aufsatz façade varies from other types of façades where mullions and transoms are not aluminium members. The auxiliary structure's members are mostly steel or wood, and their combination with aluminium enables a range of unique solutions both aesthetically and technically.

2.2.1.4 Façade type VEC

This system replaces the exterior aluminium profiles with structural silicone with high adhesion that attaches glass to interior aluminium profiles. Structural silicone is responsible for transmitting loads to the aluminium structure. In order to guarantee the protection and safety of the glasses, additional support pieces are placed in the fixing system. This system results a reduction of the façade load and an aesthetic effect with a transparent façade and glass as a main element. The manufacturing process of this type of systems includes restricted control measurements as well as maintenance during its service phase, problems of aging, surface cleaning and water tightness are fundamental points that must be addressed and considered.



Figure 23: Aufsatz façade; Aluminium - Wood (WikiMartifer, 2019)



Figure 24: Façade VEC (Navarra, 2018).

2.2.2 Ventilated façade systems

This type of façades consists of exterior coating system separated from the main structure creating air barrier, allowing a natural and continuous ventilation. This effect called chimney effect when air enters cold from the inferior, circulate and leaves heated from the superior.

The main advantages of ventilated façade are avoiding humidity and condensation, contributing to energy savings and reducing the risk of early degradation of materials giving the building a higher quality and thermal comfort. The fixing system is the supporting structure which consists of vertical and horizontal members, generally aluminium or stainless steel. The exterior material used, can be Ceramics, stone or glass.



Figure 25: Chimney effect (WikiMartifer, 2019)

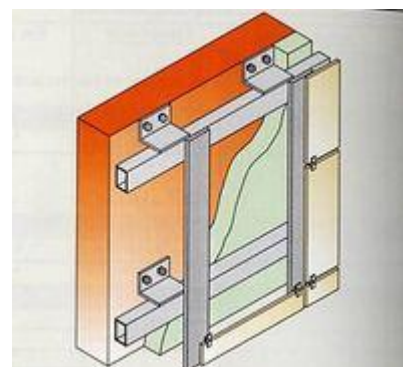


Figure 26: Fixing members (WikiMartifer, 2019)

The glazed ventilated façade, also called double skin façade, consists of two curtain walls, that is, a curtain façade on the outside and another on the inside. This system consists of double-glazing support on the inner cloth, followed by an air chamber and a single glass placed on the outer face of the support profiles. It may also include a shutter or other elements in the air chamber. The objectives of a double glass façade refer to the visualization of the external environment of the building, access to natural light, improvement of acoustic conditions, natural ventilation of the interior of the building, reduction of energy consumption with cooling or caulking, among others.

The most common system for the application of a ventilated façade in ceramic is composed of a support profile that is fixed to the wall panel duly insulated from the outside. The panels are subsequently coupled to metal member fittings.

Now a day's architecture shows an increasing interest in the façades ventilated with stone, an application of high aesthetic value and with unparalleled thermal insulation capability. In this type of coating, the joints are almost always in top and they don't provide water tightness. These panels may only be watertight if the fixing system make them independent of the wall and if the air barrier formed between the coating and the support is vented. The maximum size of the stone shall not exceed 1.40 m, the building's height shall be less than 28 m and the maximum surface of the stone shall not exceed 1 m².

The principal's advantages of a ventilated façade system are energy saving by having an excellent thermal insulation, protection against humidity by being watertight and environment friendly.

Chapter 3

3 London Dock building C1 Project

3.1 Architecture

The ongoing project in Martifer Alumínios Building C1 – London Dock located in Gauging square, London, UK. It's a residential story tower with 27 floors above ground and 96.39m height. Designed by architect Patel Taylor and developed by St. George.

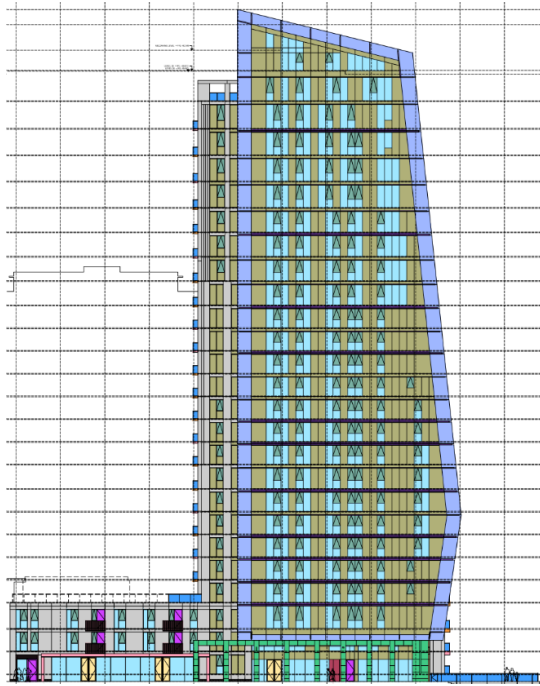
Throughout the project Martifer Alumínios is responsible for designing, manufacturing and assembling of approximately 7500 m² of unitized curtain wall, 2450 m² of stick system, 700 m² of glass fins, 600 m² of stone, 250 m² of canopies and balconies.



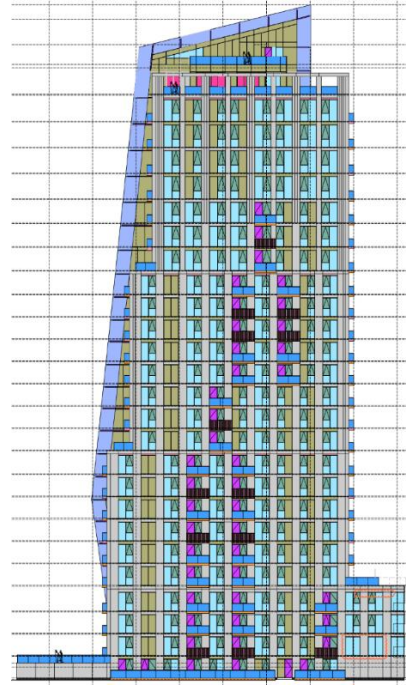
Figure 27: St George, London Dock, Building C1 (Berkeley, 2019)

West and east elevations in Figure 28 a) and b) are composed of unitized façade system which is a modular curtain wall with units consists of fixed glazing, opaque panels, windows and doors. In addition to that east elevation is provided with cladding of GRC, this solution will provide a thermal insulation, weather resistance and improve the appearance of the building. Behind the GRC panels the modular unit is finished with aluminium sheet of 3mm thickness.

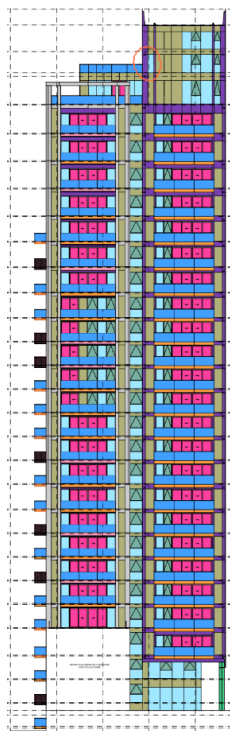
North and south elevations in Figure 28 c) and d) are mostly composed of balconies with stick façade system which is a traditional curtain wall where aluminium mullions and transoms are assembled in site with the rest of the filler material, and balconies platforms are provided by another subcontractor.



a)



b)



c)



d)

Figure 28: London Dock building C1. a) Elevation - West; b) Elevation - East; c) Elevation - North; d) Elevation - South (Berkeley, 2019)

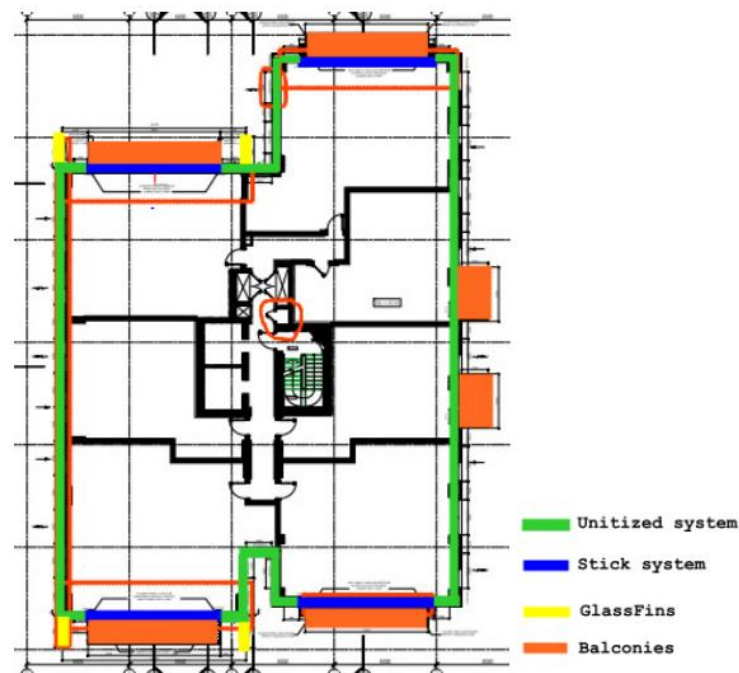


Figure 29: Typical floor Plan - London Dock Building C1 (©Martifer, 2019)

The unitized façade system has two types, West façade Figure 28 a) is designed with a capless aluminium modules where glass is fixed with structural silicone exteriorly with the interior aluminium profiles creating a structural joint of 22mm between every module. East façade Figure 28 b) is designed with a capped structural joint between modules where glass is fixed to the interior aluminium profiles by an exterior aluminium members.

3.2 Façade preparation

The façade preparation for London Dock Building C1 is one of the duties of Martifer Alumínios to design, fabricate and install at the site, involves several functions and activities that aim to develop the approved solutions for application on site. During all the phases of preparation there are activities to be carried out by the team responsible of the work and, in this sense, this subchapter exposes these works executed and how these relate to all other specialties and departments parallel to the project.

Computer's software assists and accelerates the process of preparation. One of the main programs used in this job is AutoCAD through sheet set mode where all the related drawings are available in a shared network with their layouts, all contains external references for the project details to make it easier for major modifications. AutoCAD allows the creation of manufacturing plans and approval

drawings , organization of plans and details, and all other particularities of the work related to drawing.

Other computer tools, both for the preparation of frames and for the manufacturing plans of sheets, are FPpro, PlanIQ and AlphaCAM, which are software that allows the creation of a digital model in order to obtain optimizations of materials, machining rates, construction methods and 3D visualizations that allow a better perception of the final product, in this aspect, also aided by the SolidWorks program.

For the management and logistics of all resources related to the work, materials and humans, IMS and SAP programs are used to consult available material, face-to-face punching and workmanship at the manufacturing level.

3.2.1 Design phase

Martifer's Design team provides the clients with constructive solutions for the façade and the cladding system of the building, then the chosen solution should be approved. Every structural or non-structural member must be designed and sized, all the calculation of profiles considering loads and combination that represent physical condition of the construction must be approved before starting the manufacturing process. Materials also must be chosen and approved after computer simulations that describe the material behaviour, obtained by a third party in thermal and acoustic issues for instance.

All the design details with its own calculation is in a series of documents submitted from Martifer Alumínios to client with a specific time schedule to be approved.

3.2.2 Approval phase

An approval drawing is a drawing in which the proposed solutions are transmitted to the client in accordance with the project specifications. These drawings are evaluated by the customer, subsequently require approval with the classification "A" (Approved), "B" (Approved, needs minor modifications) or "C" (Disapproved). Only those drawings classified as "A" are considered to be approved and, when the classification is "B" or "C", the drawings are subject to a new approval, once corrected. Any major modification has to be calculated and approved by the design team first, like any change in the structural conditions, materials or the thermal conditions in drawing. Approval drawings and documents include the calculation documents, material technical sheets, plans, elevations, sections and details.

When any doubt arises regarding the specifications required by the client or architecture, documents are prepared that address the resolution of a specific urgency problem. These documents, called "RFI's", consist of the exposure of the doubt or inaccuracy in question and attached files that help to better understand the problem. This process of communication between companies is carried out by a digital platform called "ACONEX", which assists the management of documents.

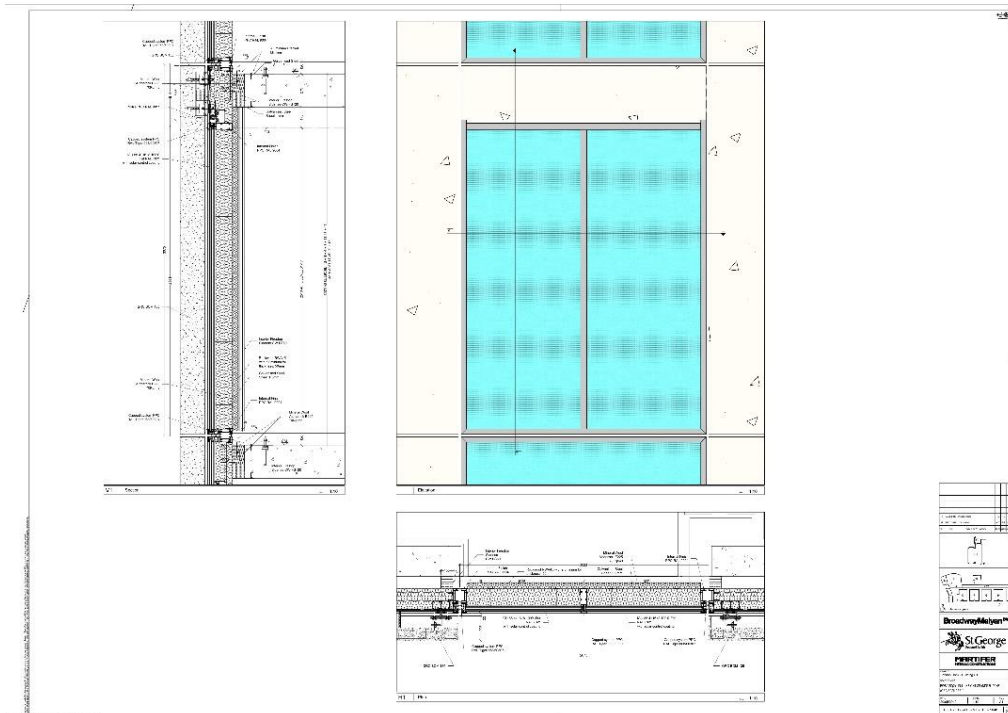


Figure 30: Approval drawing of a modular unit details (©Martifer, 2019)

3.2.3 Manufacturing phase

A manufacturing plan (PF) is a set of drawings that contain the information necessary for the manufacture of a particular module, sheet, frame or part of the work. Usually, their realization is intended to indicate measures, notches or specific connections, machining of profiles or plates, sheet bending, drainage, details and detailed information of all the materials.

The process of drawing up a PF initially begins in AutoCAD. Subsequently, depending on the type of PF, a model is created through specific computer software, which allows to obtain the best optimization of the material, machining rates and a cutting list, which informs the factory worker the correct way to proceed. cutting of the raw materials, whether they are sheets or profiles. For example, in case of cutting a sheet, optimization will help choose the right size of sheets to cut for

less material waste. Computer software also helps with making a time frame for executing and manufacturing the requested job.

After all this informative and auxiliary work has been prepared, the logistics part of the PF is made, listing the available material required for the manufacture of the PF. If any material required for the manufacturing plan is missing, it is possible to transfer material from a subcontractor. This entire process is aided by software Plan IQ, IMS and SAP, which allow better management of company resources. The approval of all the jobs have been prepared is from the factory responsible, by approving PF, it will be sent to the factory to start its manufacturing phase.

One of the frequent manufacturing plans are galvanized steel sheet plans, and producing these plans includes a series of tasks starting by designing in AutoCAD the requested sheets with their specific dimensions in a flattened state, marking the cut and folding zones, provide the sheet with requested screw holes and prepare a self-control sheet for the sheets to be labored in the factory. Each sheet will be referenced with its dimensions and quantity in a management document called Job Summery. The necessary material in this job has be shipped and stored, for that a shipping list and a list of requirements have to be issued to inform the purchasing team and quantify the required materials.

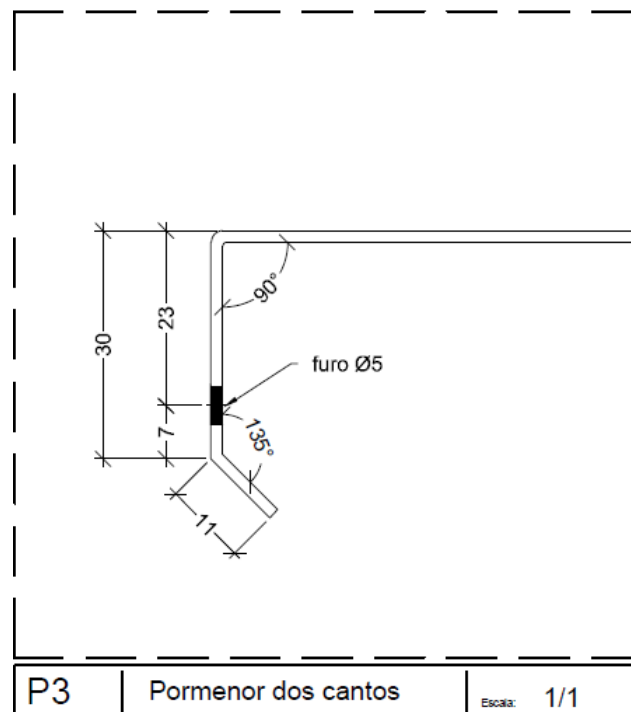


Figure 31: Galvanized steel sheet Details - Manufacturing plan (@Martifer, 2019)

The production of flat aluminium sheets with screw holes in Martifer's factory is made by a CNC (Computer Numerical Control) machine that can identify with the assistance of AlphaCAM computer software the positions of holes in the sheet by identifying the design lines and their layers in AutoCAD. Using the CNC machine increases the job efficiency by saving time, providing a higher secure working conditions and decreasing the errors range.

3.2.4 Installation phase

Cast-in channel system has been installed all over the slab edges during the structural execution, and the installation phase starts with the installation of the brackets. For that the edges of the slab must be protected by a safety system and safety net, because of the high risk of falling in this activity.

After making sure that cast-in channel is properly cleaned, T bolts will be inserted on the bracket and rotated to ensure that it is prefixed to the Cast-In insert channel. The bolt mark must be perpendicular to Cast In. Brackets must be fixed according to their tolerances and the bolts are tightened to the correct torque.



Figure 32: Brackets installation Procedure (©Martifer, 2019)

Chapter 4

4 Fire resistance of aluminium mullion

This chapter will elaborate in the fire design of a mullion in a specific aluminium module from the project London Dock Building C1 mentioned in chapter 3.



Figure 33: Module – 3D (©Martifer, 2019)

The studied module is composed of two opaque panels closed from the internal surface by two galvanized steel sheets and filled with mineral wool in between those two. All of these filler materials are fixed to aluminium transom, then the last one is fixed to mullion. The module is manufactured and assembled in the factory to be ready for installation in site.

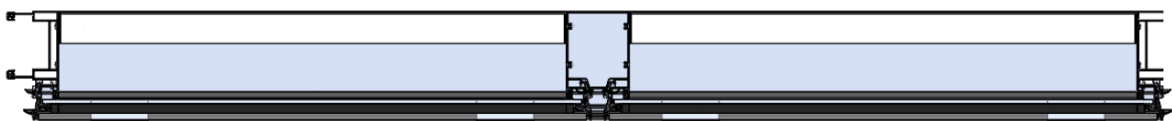


Figure 34: Horizontal Section - Module (©Martifer, 2019)

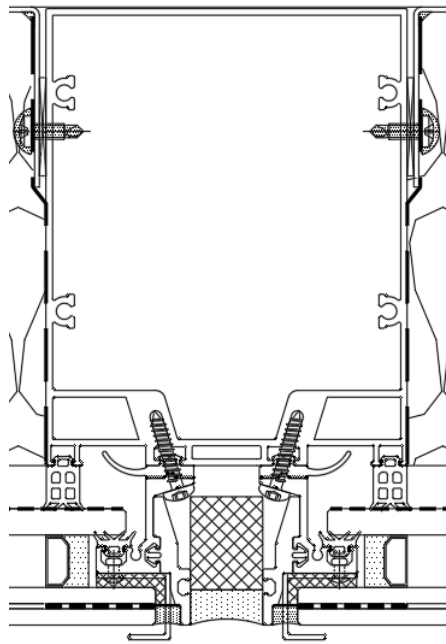


Figure 35: The studied mullion – Detail (©Martifer, 2019)

The studied section Figure 36 is painted with color RAL9004, and the following Table 12 contains the geometrical and mechanical properties of it. The information in Table 12 is according to the designing document of aluminium profiles in London Dock building C1 project.

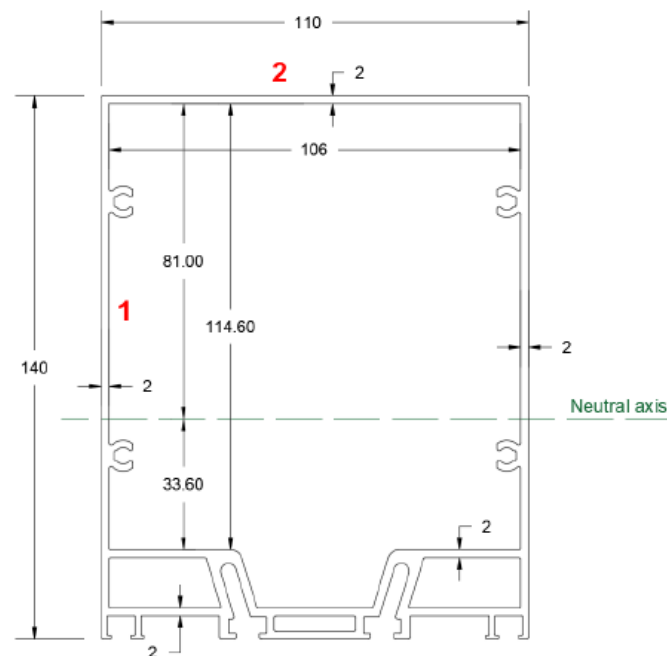


Figure 36: The studied mullion – Dimensions (©Martifer, 2019)

Table 12: Mullion - technical sheet

Alloy	EN AW-6063 T6	
f_o	160	MPa
f_u	195	MPa
Buckling Class	A	
Area	1484	mm ²
I_x	289.9	cm ⁴
I_y	261.44	cm ⁴
W_x	46.42	cm ³
W_y	46.51	cm ³
Cross-section Class	4	
A_{eff}	1351	mm ²
$I_{x,eff}$	322.67	cm ⁴
$I_{y,eff}$	238.6	cm ⁴
$W_{x,eff}$	36.12	cm ³
$W_{y,eff}$	42.31	cm ³

4.1 Fire action

A fire scenario is a description of the course of a fire with time identifying key events that characterise it and differentiate it from other possible fires. It defines the fire growth process; the fully developed stage includes the building environment and systems that will impact on the course of the fire (F. Wald, 2008).

One of the consequences of a fire action is the indirect internal forces and moments caused by thermal expansion in constructive and structural elements. The first step of quantifying the action would be define the relation between time and temperature represent the fully developed fire in a compartment.

4.1.1 Nominal fire

It's defined as standard temperature-time curve and it shows the function of temperature in time using the simple following formula completely independent from the dimensions or the type of building, illustrated in Figure 37 adapted from Ref. (Vila Real, Incêndio em Estruturas Metálicas, 2003).

$$\theta_g = 20 + 345 \log_{10}(8t + 1) \quad (6)$$

Where (θ_g), the gas temperature in the fire compartment in °C and (t) is time in minutes.

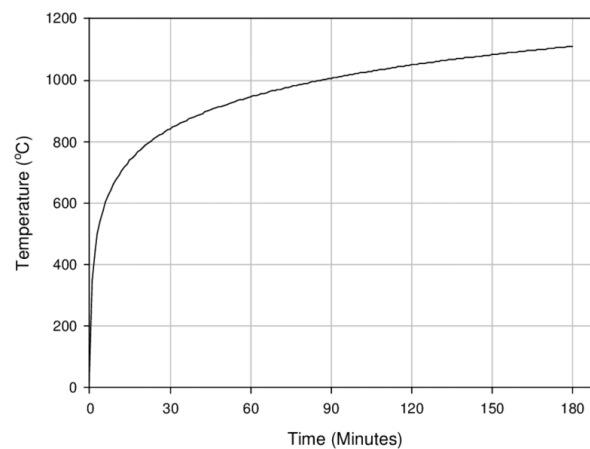


Figure 37: Time-Temperature Curve ISO 834 (ResearchGate, 2019)

ISO 834 curve is considered the reference to establish the concept of the regulatory resistance against fire and is normally the nominal fire that is considered when the required fire resistance of a construction member known as $t_{fi,req}$ is defined by the fire safety regulations.

4.1.2 Natural fire

A real fire action is controlled by three factors: the heat source, combustible and oxygen. It occurs in 4 main stages represented in Figure 38 adapted from Ref. (Vila Real, Incêndio em Estruturas Metálicas, 2003):

- The initial stage when the combustible material and oxygen are heated enough for the combustion to occurs. This stage is not included in nominal fire curves, because it does not affect the security of the structural elements. However, it has critical impact on human life because of the toxic gases produced during this stage.
- The propagation stage when fire spreads through radiation or direct contact, begins with a phenomenon known as Flashover temperature below the ceiling reach to 450 to 600 °C, and after this moment the temperatures will rapidly increase.

- c) The fully developed stage when the combustible materials burns out and leave the temperatures practically constants.
- d) The cooling stage when the temperatures decrease by the leak of combustibles, oxygen or any human security act.

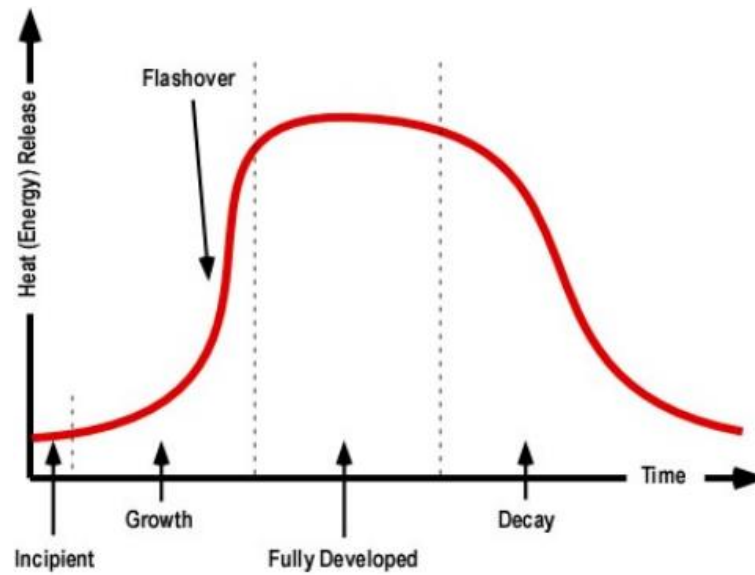


Figure 38: Natural fire stages Curve (TimberFirst, 2013)

4.2 Mechanical actions produced by a fire scenario

Fire is considered an accident action where the design value of effect of fire situation, $E_{fi,d,t}$, is obtained by the following accident combination as defined in (EN1990, 2005).

$$\sum G_k + \psi_{1,1} Q_{k,1} + \sum \psi_{2,i} Q_{k,i} + \sum A_d \quad (7)$$

Where G_k is the characteristic value of permanent action or dead loads, $Q_{k,1}$ is the characteristic value the main variable action, ψ is the combination coefficient associated to the variable action and $\sum A_d$ is the design value of indirect fire action such as forces resulting from the thermal expansion.

For the aim of simplifying the calculation, EN 1993-1-2 presents the value of $E_{fi,d,t}$ as percentage η_{fi} of the actions design value at normal temperature E_d .

$$E_{fi,d,t} = \eta_{fi} E_d \quad (8)$$

η_{fi} is the reduction factor for the design value of loads under a fire situation, in another form given in the following expression.

$$\eta_{fi} = \frac{\text{Combination in a fire situation}}{\text{Combination at 20 °C}} = \frac{G_k + \psi_{1,1} Q_{k,1}}{\gamma_G G_k + \gamma_{Q,1} Q_{k,1}} = \frac{1 + \psi_{1,1} \xi}{\gamma_G + \gamma_{Q,1} \xi} \quad (9)$$

γ_G and $\gamma_{Q,1}$ are the partial coefficients of security in permanent and variable actions in 20 °C, with given values of 1.35 and 1.5. and ξ is the ratio of loads, equals to $Q_{k,1} / G_k$.

The reduction factor η_{fi} in the followed expression defined by factors depend on the type of load, listed in Table 13. For simplification η_{fi} can be considered equal to 0.65 except for category E when 0.7 is the recommended value (EN1993-1-2, 2005).

Table 13: Load categories (Vila Real, Incêndio em Estruturas Metálicas, 2003)

Category	Load type areas
Category A	Domestic, residential
Category B	Office
Category C	Congregation
Category D	Shopping
Category E	Storage

4.3 Aluminium members temperature $\theta_{al, d}$ estimation

EN 1999-1-2 presents simplified equations to calculate the evolution of temperatures in aluminium members. These equations based on the hypothesis of the uniformity of temperatures in an aluminium section's member.

Aluminium members in construction can be protected or unprotected members, it's an important aspect to define the surface emissivity of the member and define the section factor that represent the ratio between the exposed surface area and the volume of aluminium. These factors are important to obtain the temperature of the aluminium member in a fire action.

4.3.1 Simplified equation for Non-protected member

$$\Delta\theta_{al}(t) = k_{sh} \frac{1}{c_{al} \rho_{al}} \frac{A_m}{V} \dot{h}_{net} \Delta t \quad (10)$$

Where, k_{sh} is the correction factor for the shadow effect from 4.2.3.1 in EN 1999-1-2, A_m/V is the section factor for unprotected aluminium members (m^{-1}) and some of its values listed in Table 14,

\dot{h}_{net} is the design value of the net heat flux per unit area, see (EN1991-1-2, 2002), c_{al} is the specific heat of aluminium ($c_{al} = 0,41 \theta_{al} + 903$) (J/(kg.°C)) and ρ_{al} is the aluminium density.

According to EN 1991-1-2, \dot{h}_{net} is calculated by the following expression.

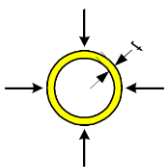
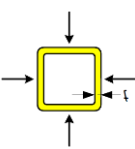
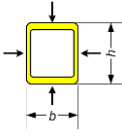
$$\begin{aligned}\dot{h}_{net} &= \dot{h}_{net,c} + \dot{h}_{net,r} \\ \dot{h}_{net,r} &= \phi \varepsilon_m \varepsilon_f \sigma [(\theta_r + 273)^4 - (\theta_m + 273)^4] \\ \dot{h}_{net,c} &= \alpha_c (\theta_g - \theta_m)\end{aligned}\quad (11)$$

Where, ϕ is the configuration factor (=1), ε_m is the surface emissivity of the member (0.3 for clean surface and 0.7 for painted surface), ε_f is the emissivity of the fire (=1), σ is the Stephan Boltzmann constant ($=5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$), θ_r is the effective radiation temperature of the fire ambient (°C) ($=\theta_g$), θ_m is the surface temperature of the member (°C) and α_c is the coefficient of heat transfer by convection (25 W/(m²K) for the ISO 834 standard fire curve)

For I sections under nominal fire actions, K_{sh} equals to $0.9 \frac{(A_m/V)b}{A_m/V}$, where $(A_m/V)b$ is the box value of the section factor. For other cases K_{sh} equals to $\frac{(A_m/V)b}{A_m/V}$. However, ignoring the shadow effect by considering ($K_{sh} = 1$) leads to conservative solutions.

Table 14 shows A_m/V for fire exposure in 4 sides of the section.

Table 14: Section factor A_m/V for unprotected structural aluminium members (EN 1999-1-2)

Tube exposed to fire on all sides		$\frac{A_m}{V} = \frac{1}{t}$
Hollow section exposed to fire on all sides		If $t \ll b$: $\frac{A_m}{V} = \frac{1}{t}$
Box section exposed to fire on all sides		$\frac{A_m}{V} = \frac{2b + h}{\text{Cross - Section Area}}$

However, for the studied aluminium section Figure 36, fire exposure is considered in one side, A_m/V in this case is equal to the perimeter exposed to fire divided by the total section area. For section area equals to 1484 mm^2 and fire exposure in one side 110 mm , A_m/V for the studied section is 74.12 m^{-1} . As the profile is designed to be finished with paint type RAL 9004, the surface emissivity ε_m equals to 0.7.

Using equation (10) and its boundary conditions (11), nomograms can be built to obtain the temperature of unprotected and protected aluminium profiles function of the section factor, as the one presented in Figure 39, taken from ref. (Vila Real, Lopes, & Pinho-da-Cruz, ESTRUTURAS DE ALUMÍNIO: NOMOGRAMAS PARA O CÁLCULO DA SUA RESISTÊNCIA AO FOGO DE ACORDO COM O EUROCÓDIGO 9, 2011).

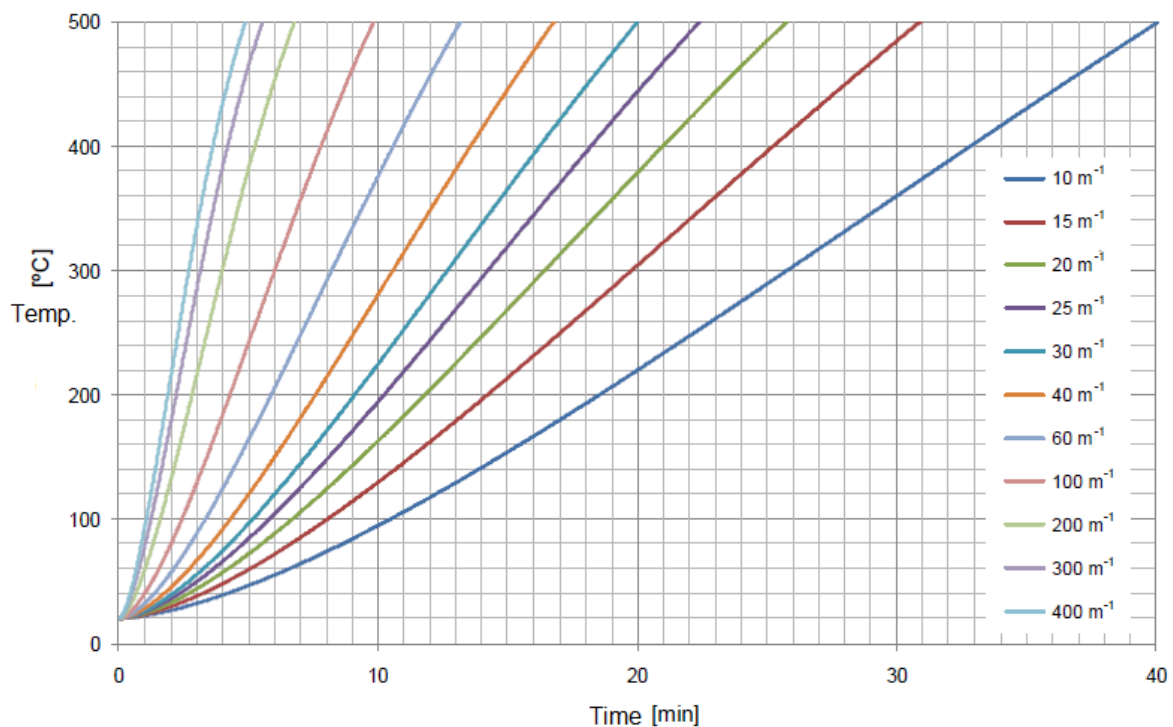


Figure 39: Nomogram to obtain the temperature of unprotected aluminium profiles with clean surface ($\varepsilon_m = 0,7$), subjected to the ISO 834 curve, for different values of $k_{sh} A_m/V$ (Vila Real, Lopes, & Pinho-da-Cruz, ESTRUTURAS DE ALUMÍNIO: NOMOGRAMAS PARA O CÁLCULO DA SUA RESISTÊNCIA AO FOGO DE ACORDO COM O EUROCÓDIGO 9, 2011)

In this dissertation an excel spreadsheet was developed to obtain the temperature evolution of the analysed profile (see Table 15).

The followed Table 15 and Figure 40 conclude that the temperature of the studied mullion considering a uniform distribution of temperature in the section in a nominal fire action (ISO 834) exposed on one side reaches to 500 °C in approximately 12 minutes for unprotected member.

Table 15: Excel Sheet's resume for Aluminium temperature Calculation – without protection

t(min)	θ_g (°C)	ϵ_m	h_{net}	$c_{al}(J/(kg.K))$	A_m/V (m ⁻¹)	$\Delta\theta_{al}$ (°C)	$\Delta\theta_{al}$ (°C)
0.000	20.00	0.7	0.00	911.20	74.12	0.000	20.000
0.017	38.75		551.23	911.20		0.017	20.017
0.033	55.42		1054.20	911.21		0.032	20.048
0.050	70.41		1518.45	911.22		0.046	20.094
0.067	84.04		1950.89	911.24		0.059	20.153
-	-		-	-		-	-
11.567	699.98		26723.41	1106.65		0.663	497.360
11.583	700.20		26695.34	1106.92		0.662	498.022
11.600	700.41		26667.20	1107.19		0.661	498.683
11.617	700.62		26638.99	1107.46		0.660	499.344
11.633	700.84		26610.70	1107.73		0.660	500.003

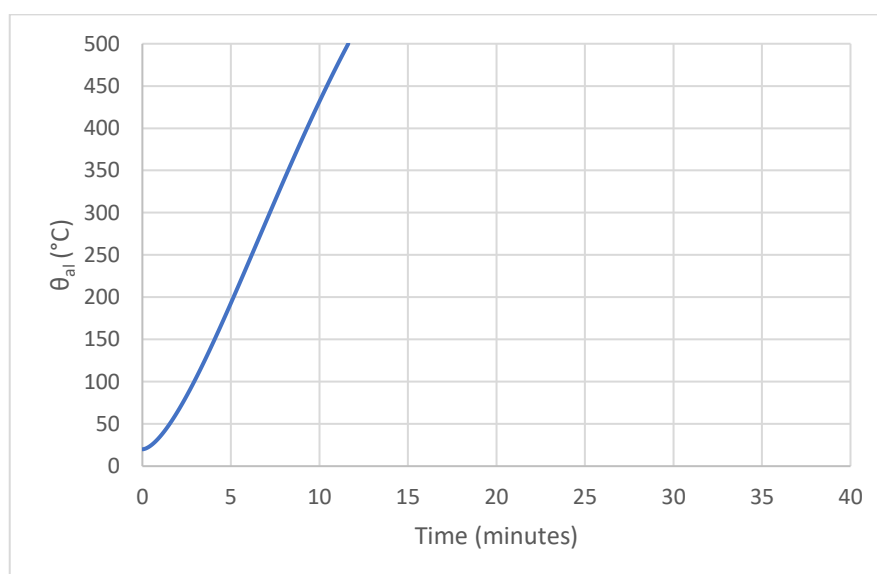


Figure 40: Aluminium Temperature - Time Curve (Without protection)

According to Table 7, and by reaching to 500 °C, aluminum alloys will have the value 0 for $k_{0,\theta}$, which means a total collapse for all the alloys given in the table.

4.3.2 Simplified equation for Protected member

$$\Delta\theta_{al}(t) = \frac{\lambda_p/d_p}{c_{al}\rho_{al}} \frac{A_p}{V} \left[\frac{1}{1+\phi/3} \right] [\theta(t) - \theta_{al}(t)]\Delta t - (e^{\phi/10} - 1)\Delta\theta(t) \quad (12)$$

Where, A_p/V is the section factor for aluminium members insulated by fire protection (m^{-1}), $\theta(t)$ is the ambient gas temperature at time t ($^{\circ}C$), $\theta_{al}(t)$ is the aluminium temperature at time t ($^{\circ}C$) and

$$\phi = \frac{c_p \lambda_p}{c_{al} \rho_{al}} d_p \frac{A_p}{V}.$$

The protection considered in project is a 50mm of mineral wool one side exposed to fire. The product is ROCKWOOL RWA45 with thermal conductivity of 0.035 (W/(m.K)), density of 45 (kg/m³) and specific heat capacity of 840 (J/(kg.K)). It provides the member with good thermal insulation, and this material is non-combustible.



Figure 41: Insulation – RWA45 (@RockWool, 2019)

Taking into consideration the nominal fire scenario with Δt equals to 30 seconds (According to EN 1999-1-2 Δt must be ≤ 30 seconds), in addition to the specification and properties of protection mentioned before and through an Excel sheet, the temperature of aluminium was calculated using equation (12). The following table and graph are a resume of the calculation process.

Table 16: Excel Sheet's resume for Aluminium temperature Calculation – with protection

t(min)	θ_g (°C)	c_{al} (J/(kg.K))	A_p/V (m ⁻¹)	ϕ	$\Delta\theta_g$ (°C)	$\Delta\theta_{al}$ (°C)	θ_{al} (°C)
0	20.00	911.2	74.12	0.05694	0.000	0.00000	20.00
0.5	261.14	911.2		0.05694	241.145	0.00000	20.00
1	349.21	911.2		0.05694	88.069	0.00000	20.00
1.5	404.31	911.2		0.05694	55.097	0.00000	20.00
2	444.50	911.2		0.05694	40.194	0.03405	20.03
2.5	476.17	911.2		0.05694	31.661	0.10242	20.14
3	502.29	911.3		0.05694	26.124	0.15019	20.29
3.5	524.53	911.3		0.05694	22.238	0.18608	20.47
4	543.89	911.4		0.05693	19.360	0.21440	20.69
-	-	-		-	-	-	-
178	1108.07	983.9		0.05274	0.421	0.52225	197.78
178.5	1108.49	984.1		0.05273	0.420	0.52209	198.31
179	1108.90	984.3		0.05271	0.419	0.52193	198.83
179.5	1109.32	984.5		0.05270	0.418	0.52176	199.35
180	1109.74	984.7		0.05269	0.416	0.52159	199.87

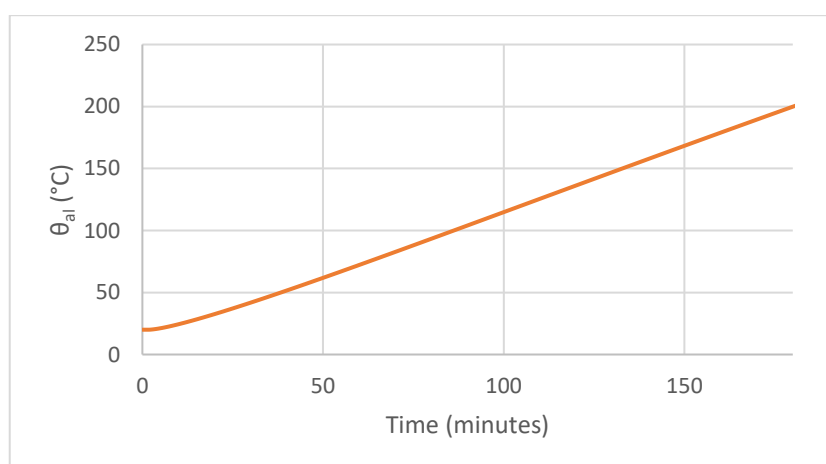


Figure 42: Aluminium Temperature - Time Curve (With protection)

Table 16 and Figure 42 conclude that the temperature of the studied mullion considering a uniform distribution of temperature in the section in a nominal fire action (ISO 834) exposed on one side reaches to approximately 200 °C in 180 mins for the protected studied member.

4.4 Fire Resistance checking domains

Fire resistance classes are the classification of building components and materials, each element is specified by its class that defines different performance criteria. A construction element can be classified by one or a combination of the following classes (RISE, 2019).

R – load bearing capacity is the ability of construction element to resist a fire exposure on one or several sides while supporting an external load during a period of time without losing its stability. The performance criteria tested for this fire resistance class is the rate of deformation and maximum deformation.

E – Integrity is the ability of a separating construction element exposed to fire on one side, to prevent the passage of flames and gases through it and reaching to the unexposed side.

I – Insulation is the ability of separating construction element exposed on one side, to restrict the temperature rise on the unexposed side below the specified levels.

There are more fire resistance classes with several requirement such as radiation, mechanical action, self-closing, smoke leakage and covering. Normally the fire resistance classification is followed numbers as a time limit in minutes (15, 30, 45, etc.) which shows the time the performance criteria is fulfilled during a standardized fire test.

In the studied project, the fire safety design plan consists of cavity barriers. Approved document B has the regulations for fire safety in the United Kingdom and it defines cavity barriers as “A construction, other than a smoke curtain, provided to close a concealed space against penetration of smoke or flame, or provided to restrict the movement of smoke or flame within such a space” (HMGovernment, 2010). Building C1 in London Dock is provided by horizontal barriers at compartment lines classified with 120 minutes fire resistance for integrity and insulation (EI120), vertical barriers are classified with 60 minutes fire resistance for integrity and insulation (EI60).

In addition to that, the fire-resistant material RockWool – RWA45 provides every modular unit with steel sheet internal finish in façade with 60 minutes of fire stopping (Integrity and Insulation).

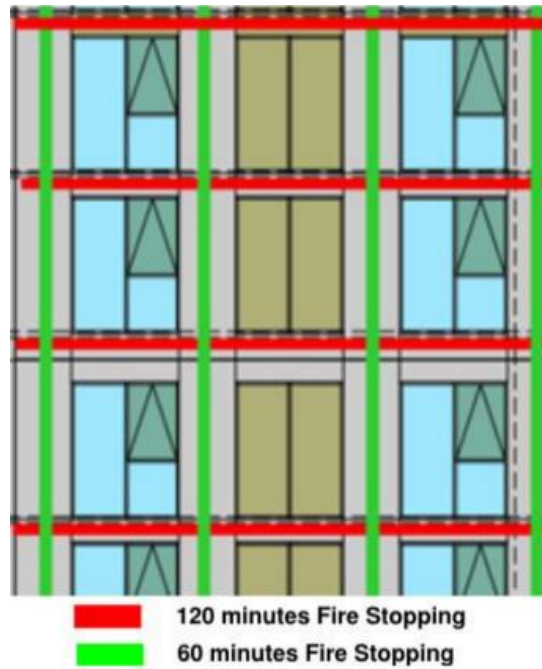


Figure 43: Fire stopping location (©Martifer, 2019)

For 120 minutes of fire exposure and based on the previous calculation for the studied member in Figure 42, aluminium temperature reaches to $\theta_d = 136.29^\circ\text{C}$.

The verification of fire resistance in an element can be done in 3 different domains:

- 1- Time domain: the required time for a construction element to have stability, integrity or insulation ($t_{fi,req}$) must be less or equal to the time (t_d) (Design value) when the critical temperature of the element ($\theta_{al,cr}$) is achieved.
- 2- Temperature domain: the design value of temperature (θ_d) is the temperature of the element at the required time in its classification, and it must be less or equal to the critical temperature of the element ($\theta_{al,cr}$), which is the temperature when the design value of actions in a fire situation is equal to design value of resistance capacity in a fire situation, ($E_{fi,d} = R_{fi,d}$).
- 3- Resistance domain: the design value of resistance capacity in a situation of fire ($R_{fi,d}$) must be more or equal to the design value of actions in a fire situation ($E_{fi,d}$) until the required time.

$E_{fi,d}$ is achieved by equation (8), and $R_{fi,d}$ is calculated by multiplying the design value of resistance capacity of the element in 20°C (R_d) by the reduction factor $k_{0,\theta}$ listed in Table 7.

$$R_{fi,d} = k_{0,\theta} R_d \left(\frac{\gamma_{Mx}}{\gamma_{M,fi}} \right) \quad (13)$$

γ_{Mx} is the material coefficient, and according to EN 1999-1-1, it can be $\gamma_{M1} = 1.1$ (for $N_{0,Rd}$ and $M_{c,Rd}$) or $\gamma_{M2} = 1.25$ (for $N_{u,Rd}$ and $M_{u,Rd}$).

$\gamma_{M,fi}$ is the partial safety factor for the relevant material property for the fire situation, and the recommended value for it in EN 1999-1-2 is $\gamma_{M,fi} = 1.0$.

For the studied member and according to the design team in Martifer the following Table 17 contain the values of maximum loads possible in the studied mullion in 20 °C (simply supported). The considered loads in the analysis of Martifer's team are, Dead load (Glass – $g_k = 25 \text{ kN/m}^3$, Aluminium – $g_k = 27 \text{ kN/m}^3$, Steel – $g_k = 78 \text{ kN/m}^3$), Live load (Barrier load) and wind load (1.5 kPa). The table also contain the resistance capacity values of the studied member according to Martifer's design team.

Table 17: The Design Values of the studied member (@Martifer, 2019)

N_{0,Ed}	4.00	kN
M_{y,Ed}	2.59	kN.m
M_{z,Ed}	0.05	
N_{0,Rd}	215.85	kN
M_{y,Rd}	5.25	kN.m
M_{z,Rd}	6.15	

In equation (13), the value of $k_{0,\theta}$ correspond the reduction factor at the temperature obtained for the required time, and the temperature achieved by that time (θ_d) which as mentioned before it's equal to 136.29 °C. According to Table 7 and for θ_d , the value of $k_{0,\theta} = 0.86$ (by doing interpolation for the aluminium alloy EN AW-6063 T6). The result theoretically means that this type of aluminium alloy fall to 86% of its resistance in the required time (120 minutes).

For the previous values and considering $\gamma_{M1} = 1.1$ and $\gamma_{M,fi} = 1.0$, using equation (13), the design values of resistance capacity of the studied aluminium member are listed in Table 18.

Table 18: Values of $R_{fi,d}$

N_{fi,Rd}	204.19	kN
M_{y,fi,Rd}	4.79	kN.m
M_{z,fi,Rd}	5.82	kN.m

According to equation (8), actions in an environment temperature are multiplied by a reduction factor η_{fi} which is equal to 0.65 for Category A (Residential area). The following Table 19 presents the values of the actions in the studied mullion in a fire action.

Table 19: $E_{fi,d}$ Design Values and security verification

$N_{fi,Ed}$	2.6	kN
$M_{y,fi,Ed}$	1.68	kN.m
$M_{z,fi,Ed}$	0.03	kN.m
$\frac{N_{fi,Ed}}{N_{fi,Rd}} + \frac{M_{y,fi,Ed}}{M_{y,fi,Rd}} + \frac{M_{z,fi,Ed}}{M_{z,fi,Rd}} = \mathbf{0.37} < \mathbf{1.0} \text{ OK!}$		

Chapter 5

5 Conclusions and final considerations

Aluminium having the properties such as formability, flexibility, durability and light weight is considered to be a modern construction material. However, aluminium consumes higher energy during its production phase than other building material which results higher initial costs.

By considering a general point of view or the full life cycle of building material, aluminium solutions achieve a significant and considered weight reduction which is a good structural benefit in façade construction. In addition to that and during the full life cycle of aluminium, the required maintenance costs are relatively low causing a costs and energy savings. Finally, it has been mentioned in chapter 2 that one of the unique properties of aluminium is its resistance for corrosion.

Aluminium, due to its characteristics, is infinitely recyclable without losing its physicochemical properties, making this material sustainable. Leftovers of beverage cans, aluminium foils, sheets or profiled windows can be recycled requiring only 5% of the energy initially expended.

In aluminium façades, glass is the main used material and composes most of the façade area with that glass is responsible of the energy received from the outside which makes thermal and acoustic insulation its main functionalities.

In chapter 4, it was concluded that the studied mullion without protection will collapse after 12 minutes of fire exposure. This result can be explained by the very small thickness of the studied mullion, the mullion has 2mm of thickness, therefore, a high value of section factor A_m/V is obtained, which gives also a high value of $\Delta\theta_{al}$ based on EN 1999-1-2 norms and equations.

The studied aluminium mullion with a 50mm of Rockwool layer, verified the conditions in fire resistance equations in EN 1999-1-2. The used fire protection material also protects the steel sheets in the sides of the mullion from condensation that might form corrosion over it in extreme atmosphere condition.

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